Space Power And Propulsion

Terry Kammash
Nuclear Engineering and Radiological Sciences
University of Michigan
Ann Arbor, MI 48109

presented at the workshop on
Human/Robotic Exploration of The Solar System
NASA Langley Research Center
Hampton, Virginia

November 6-7, 2001

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Man's attempt to explore the solar system and beyond requires propulsion
stems with performance capabilities that far exceed those provided by present-day
emical propulsion. High propulsive characteristics are needed since space travel is
zardous due to galactic radiation, and man is unable to endure long journeys without
periencing physical and mental degradation. A quick review of the most likely energy
urces that can meet these requirements reveals that nuclear energy whether in the form
fission reactions, fusion reactions, or matter-antimatter annihilation reactions provides
most desirable options due to the large amount of energy produced per unit mass.
ing specific impulse (I_{sp}) and thrust (F) as the two critical propulsion parameters, we
iew several propulsion concepts that have been advanced as likely candidates for near-
n application to space exploration. While solid core nuclear thermal fission systems
h as the NERVA rocket are capable of producing large thrusts, they are limited by fuel
lting to I_{sp}'s of about 1000 seconds. This temperature limitation can be ameliorated in
Gas Core nuclear rocket (GCR) where the fission fuel is utilized in a gaseous (or even
ized) form, but other serious technical issues such as containment, and fuel loss due to
dest accelerations render the system as less than a promising approach in the
eseeable future. Next to the proton-antiproton reactions, the fusion reactions utilizing
ious isotopes of hydrogen and helium as fuel do provide the largest specific energy
l constitute the basis of several fusion propulsion concepts that can produce propulsive
abilities that can easily meet the exploration challenges in the time frame of interest.
ese capabilities can also be further enhanced in some fusion concepts when modest
ounts of antimatter are used to catalyze the fusion reactions. Other concepts that show
reat near-term potential are the ultrafast laser-driven plasma propulsion systems that
m to be capable of producing $I_{sp} > 10^6$ seconds. In many of these devices, the power
rce that is needed to drive the system is likely to be a nuclear reactor coupled to a
rmal conversion system such as a closed Brayton Cycle. Several designs representing
sent-day, near-term and far-term systems utilizing advanced materials for use in the
iator components show great promise in reducing the masses of these units.
ovative ideas associated with the use of MHD generators that utilize neutrons from the
ctor to enhance their electrical conductivity (thus enabling them to replace the massive
bines in the conventional cycle) are truly a reflection of some of the ongoing
ouraging research and development in space power that can make solar-system
loration in the next few decades readily achievable.

Table 1. Yield From Various Energy Souces

Fuels	Reaction Products	Energy Release (J/kg) $(E/m_i = \alpha c^2)$	Converted Mass Fraction $(\alpha = \frac{\Delta m}{m_i} = \frac{m_i - m_f}{m_i})$
Chemical			
Conventional: (LO_2/LH_2)	Water, Hydrogen, Common Helium (He^4)	1.35×10^7	1.5×10^{-10}
Exotics: Atomic Hydrogen		2.18×10^8	2.4×10^{-9}
Metastable Helium		4.77×10^8	5.3×10^{-9}
Nuclear Fission			
U^{233}, U^{235}, Pu^{239} (~200Mev/U^{235} Fission)	Radioactive Fission Fragments, Neutrons, γ-Rays	8.2×10^{13}	9.1×10^{-4}
*Nuclear Fusion**			
DT (0.4/0.6)	Helium, Neutrons	3.38×10^{14}	3.75×10^{-3}
CAT-DD+ (1.0)	Hydrogen, Helium & Neutrons	3.45×10^{14}	3.84×10^{-3}
He^3 (0.4/0.6)	Hydrogen, Helium (Some Neutrons)	3.52×10^{14}	3.9×10^{-3}
B^{11} (0.1/0.9)	Helium (Thermonuclear Fission)	7.32×10^{13}	8.1×10^{-4}
Matter Plus Antimatter	Annihilation Radiation		
(0.5/0.5)	Pions, Muons, Electrons, Positrons } Neutrinos & γ-Rays	9×10^{16}	1.0

*Weight Composition Corresponds to a 50/50 Fusion Fuel Mixture

+CAT-DD – "Catalyzed" DD Reaction Enhanced By Burnup of Reaction Tritons (T) and Helium-3 (He^3) Nuclei with Deuterons (D) in situ

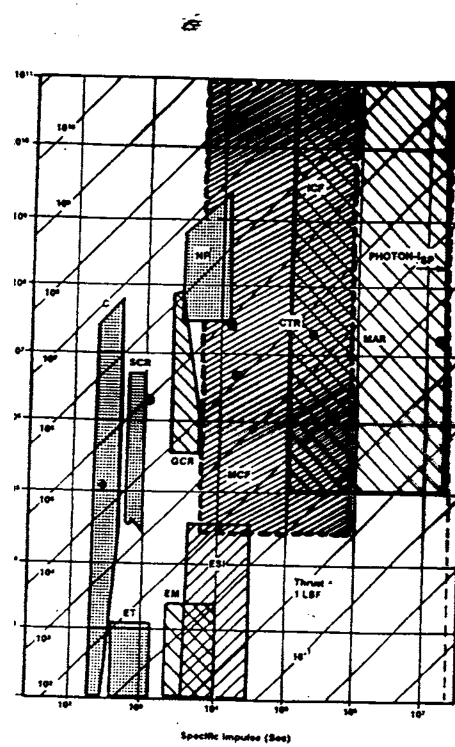
Notation: U^{233}, U^{235}, Pu^{239} - Fissile Isotopes of Uranium and Plutonium

Δm - Change in Mass Between Reactants (m_i) and Products (m_f)

B^{11} - Fusionable Isotope of Boron

p, $\bar{p}$ - Proton and Antiproton

...ions in the Use of Antimatter ...



SCR=Solid Core Reactor

GCR=Gas Core Reactor

EM=Electromagne...

ESI=Electrostat... Ion Thruste...

MCF=Mag. Confin... Fusion

C=Chemical

CTR=Controlled Thermonucle... Reactions

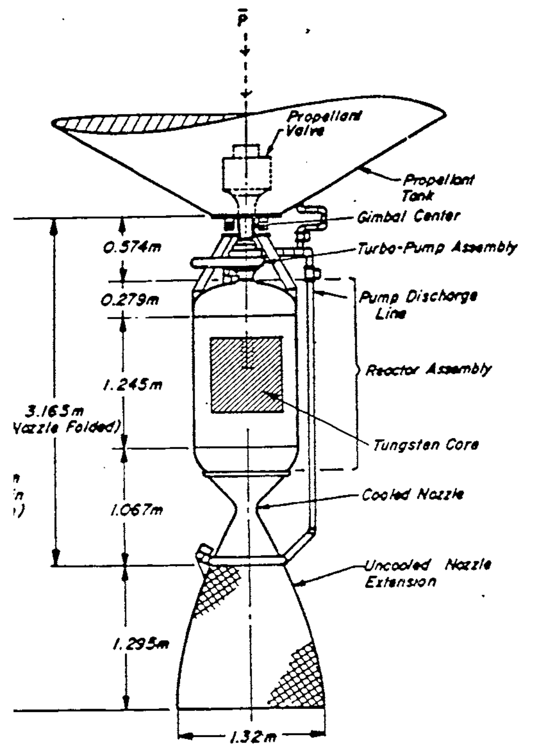
MAR=Mass Annihilatio... Rocket

EP=Electric Propulsion

ET=Electrotherm...

NP=Nuclear Pulsed (Orion Type)

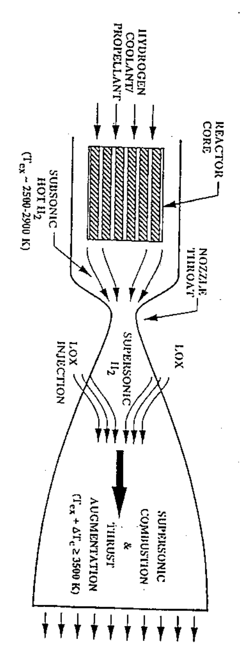
ICF=Inertial Confinement Fusion



2. Schematic diagram of the Small Nuclear Rocket Engine designed during the NERVA program. The nuclear reactor core has been replaced with a possible configuration of the metal-honeycomb used to convert the antimatter annihilation energy into heat.

2VA = Nuclear Engine for Rocket Vehicle Application

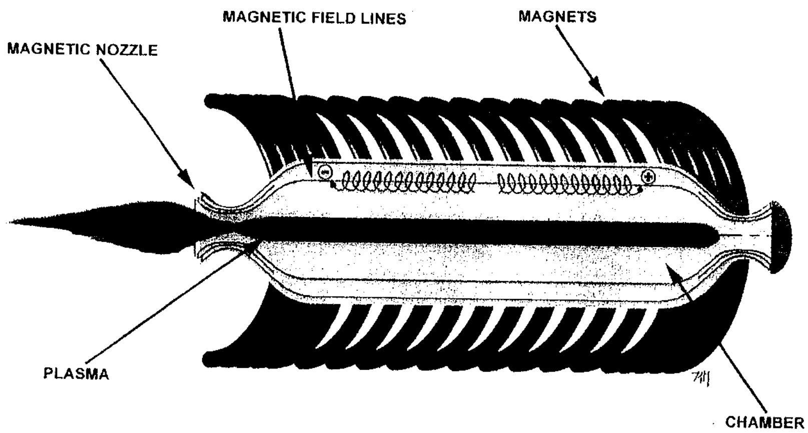
"LOX-Augmented NTR" (LANTR) Concept
--Schematic & Performance Capability--



Life (hrs.)	Isp (sec) 5	Isp (sec) 10	Isp (sec) 35	Tankage Fraction (%)	T/W_{eng} Ratio
T_c (°K)	2900	2800	2600		
O/H MR = 0.0	941	925	891	14.0	3.0*
1.0	772	762	741	7.4	4.8
3.0	647	642	631	4.1	8.2
5.0	576	573	566	3.0	11.0
7.0	514	512	508	2.5	13.1

* For 15 klbf LANTR with chamber pressure = 2000 psia and ϵ = 500 to 1

NASA Lewis Research Center



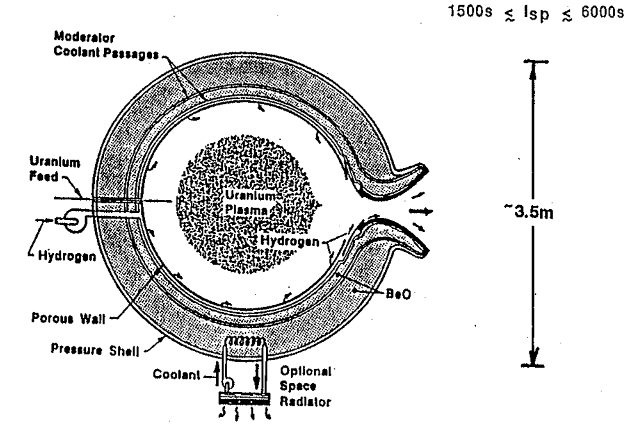
GASDYNAMIC MIRROR FUSION PROPULSION ENGINE

NASA
Lewis Research Center

"OPEN CYCLE" GAS CORE ROCKET ENGINE CONCEPT

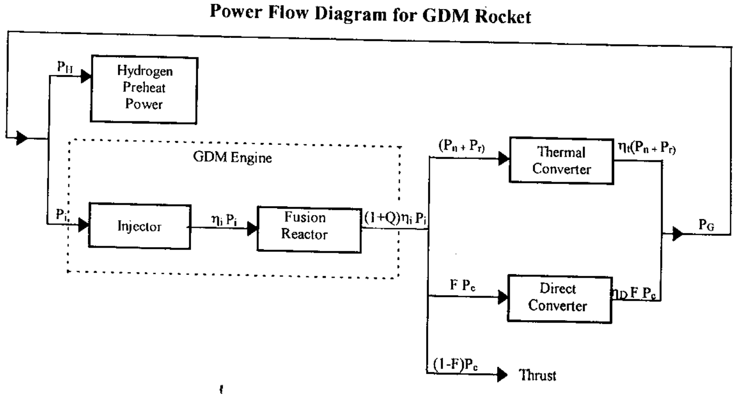
ASAO

1500s ≲ Isp ≲ 6000s



High Specific Impulse, Porous Wall Gas Core Engine. (Courtesy of NASA, Lewis Research Center)

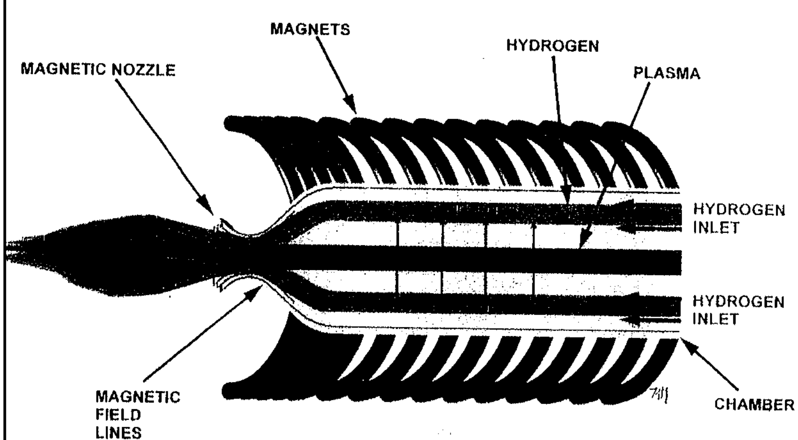
Power Flow Diagram for GDM Rocket



$$Q_c = \frac{1 - F\eta_I\eta_D}{F\eta_I\eta_D - \frac{P_H}{P_f} - \frac{(P_n + P_r)}{P_f}\eta_t(F\eta_D - \eta_I)}$$

F = fraction of charged particle power going to Direct Converter
η_I = Injector efficiency
η_t = Thermal Converter efficiency
η_D = Direct Converter efficiency

P_c = charged particle power
P_n = Neutron Power
P_r = Radiated Power, $P_B + P_S$
P_H = Hydrogen Pre-heat Power
P_G = Gross Electric Power



THRUST-ENHANCED GASDYNAMIC MIRROR FUSION PROPULSION ENGINE gdmi

Gasdynamic Mirror Fusion Propulsion (D+T)

Plasma Density	= 1.0E+16 cm^-3	Plasma Radius	= 5.0 cm
Plasma Temperature	= 10.000 keV	Mirror Radius	= 0.5 cm
Plasma Mirror Ratio	= 100.0	Halo Thickness	= 10.0 cm
Beta (vacuum)	= 0.950	Shield Thickness	= 42.0 cm
Magnetic Field B0	= 9.207 tesla	Shield-Magnet Gap	= 10.0 cm
Mean Free Path (eff)	= 1.253 m	Current Density(1)	= 50 MA/m2
Eta-tc	= 0.45	Current Density(2)	= 250 MA/m2
Eta-dc	= 0.90	<sig-v>DT	= 1.128E-16 cm^3/s

PARAMETER	eph = 0	WITH eph	UNIT
Gain factor Q	1.222	1.222	
Plasma length	43.780	54.561	m
Confinement time	4.068E-03	5.069E-03	sec
Injection Energy	16.495	20.557	keV
Electrostatic potential	0.000	9.937	keV
Thrust	2.512E+03	3.130E+03	N
Thrust power	1.351E+03	1.684E+03	MW
Injection power	2.233E+03	2.783E+03	MW
Fusion power	2.730E+03	3.402E+03	MW
Bremsstrahlung power	5.817E+01	7.250E+01	MW
Synchrotron rad power	1.894E+01	2.360E+01	MW
Neutron power	2.183E+03	2.721E+03	MW
Neutron wall load	5.291E+01	5.291E+01	MW/m2
Reactor mass (1)	311.0	387.5	Mg
Reactor mass (2)	90.8	113.1	Mg
Reactor mass (3)	55.5	69.1	Mg
Injector mass (1)	254.4	317.0	Mg
Injector mass (2)	74.3	92.6	Mg
Injector mass (3)	45.4	56.6	Mg
Engine (Recator+Inj) (1)	565.4	704.5	Mg
Engine (Recator+Inj) (2)	165.1	205.7	Mg
Engine (Recator+Inj) (3)	100.9	125.7	Mg
Thermal conv mass (1)	248.7	309.9	Mg
Thermal conv mass (2)	72.6	90.5	Mg
Thermal conv mass (3)	44.4	55.3	Mg
Direct conv mass(1)	154.0	191.8	Mg
Direct conv mass(2)	44.9	56.0	Mg
Direct conv mass(3)	27.5	34.2	Mg
Radiator mass	240.1	299.3	Mg
Total vehicle mass (1)	1208.2	1505.5	Mg
Total vehicle mass (2)	743.0	925.8	Mg
Total vehicle mass (3)	** 412.8	514.5	Mg
Specific power (1)	2.390	2.391	kW/kg
Specific power (2)	8.187	8.188	kW/kg
Specific power (3)	13.399	13.399	kW/kg
Specific impulse	1.268E+05	1.425E+05	sec
Round trip time* (1)	286.50	286.15	days
Round trip time* (2)	225.29	224.96	days
Round trip time* (3)	168.68	168.35	days

*Destination: MARS (D = 7.80E+10 m)

** Does not include Mirror Magnet of 300 mT

Mars Mission Results for Various GDM Designs

Case #	Description	Mars Rd Trip Time
1	Current system with mirror field and present day radiator $m_f = 723$ mT	222 days
2	Rotating magfield and liquid droplet radiator $m_f = 270$ mT	137 days
3	Rotating magfield and advanced CBC radiator technology $m_f = 251$ mT	132 days
4	Rotating magfield and present day radiator $m_f = 481$ mT	182 days

Radiator Dimensions and Parameter

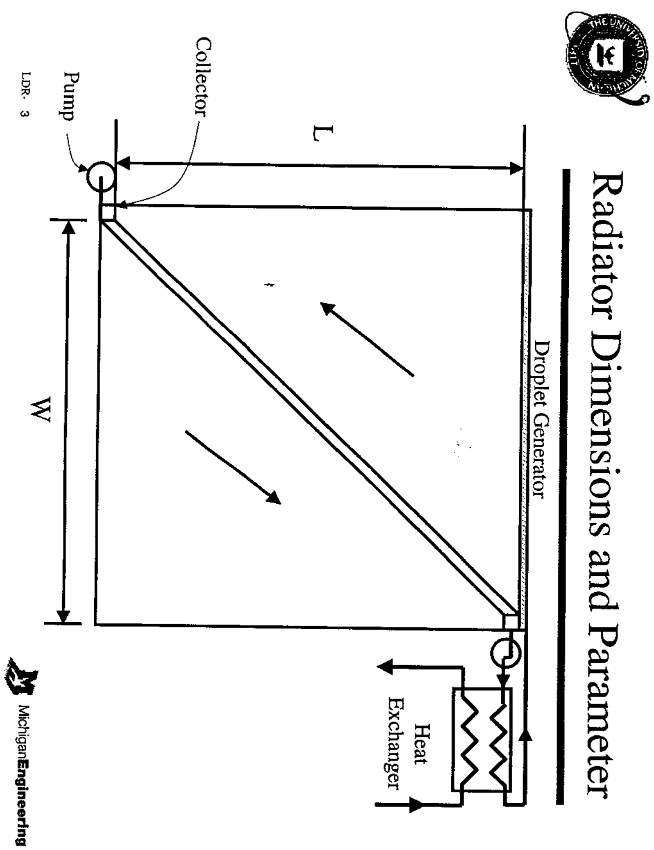
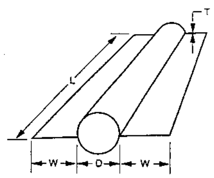


TABLE I.—CARBON-CARBON HEAT-PIPE MASS BREAKDOWN FOR THREE COMPOSITES

Material	T300	P95 WG	K 1100
Thermal conductivity, W/mK	50–80	300–500	750–1000
Heat pipe dimensions, cm			
Length, L	91.4	91.4	91.4
Shell diameter, D	2.5	2.5	2.5
Width, W	2.5	5	7.5
Thickness, T	0.1	0.1	0.1
Heat pipe components mass, g			
C–C shell	169.5	214.0	254.5
Liner with evaporator	41.2	41.2	41.2
End caps	13.1	13.1	13.1
Fill tubes	7.2	7.2	7.2
Braze	22.5	22.5	22.5
Foil wick	24.0	24.0	24.0
Working fluid	13.5	13.5	13.5
Total mass, g	291.0	335.5	376.0
One-sided radiating area, m^2	0.0691	0.116	0.16
Specific mass, kg/m^2	4.21	2.89	2.35
Two-sided radiating area, m^2	0.1382	0.232	0.32
Specific mass, kg/m^2	2.11	1.45	1.18



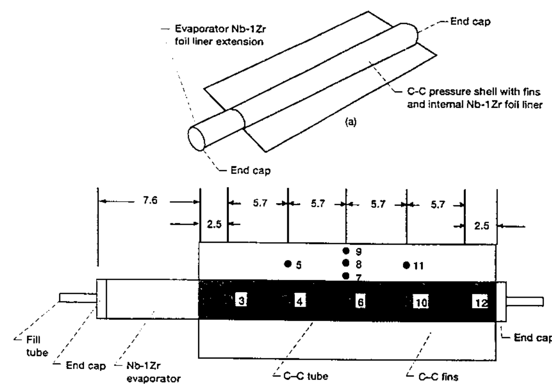
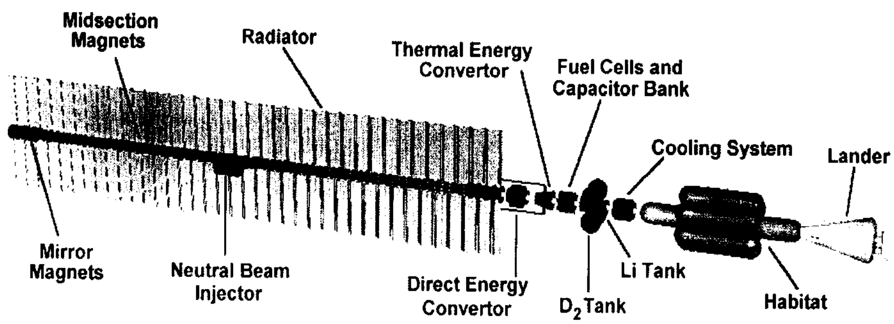


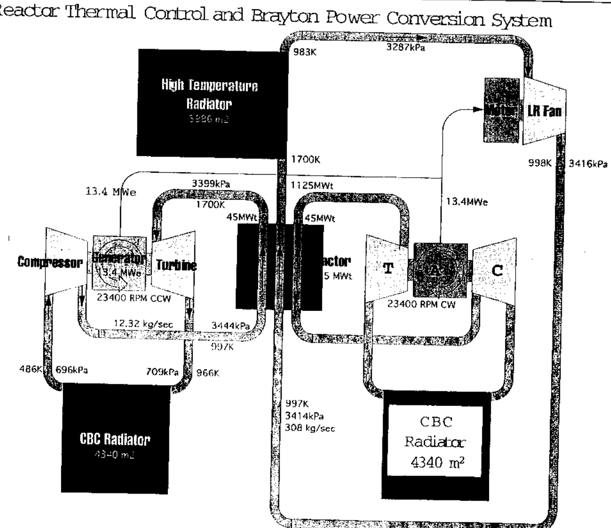
Figure 1.—Carbon-carbon heat pipe radiator element (all dimensions are in centimeters). (a) C–C shell and metallic liner/evaporator extension. (b) Top view of test article showing thermocouple locations.

INTERPLANETARY VEHICLE USING A GASDYNAMIC MIRROR FUSION PROPULSION SYSTEM



Nuclear Fusion Propulsion Vehicle

Reactor Thermal Control and Brayton Power Conversion System



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Advanced Space Transportation Team

LAD 2

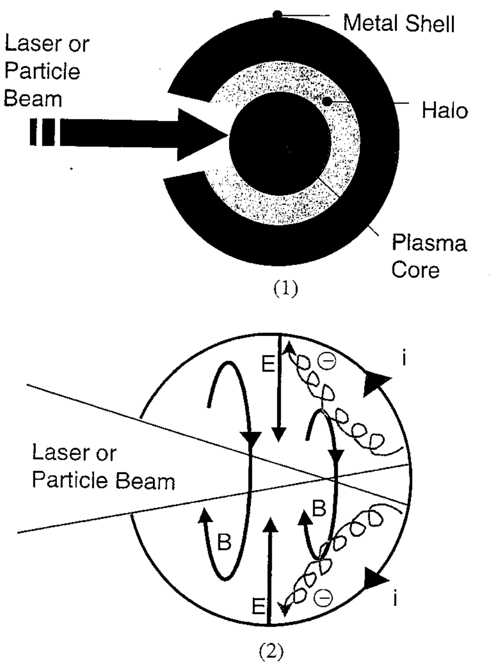
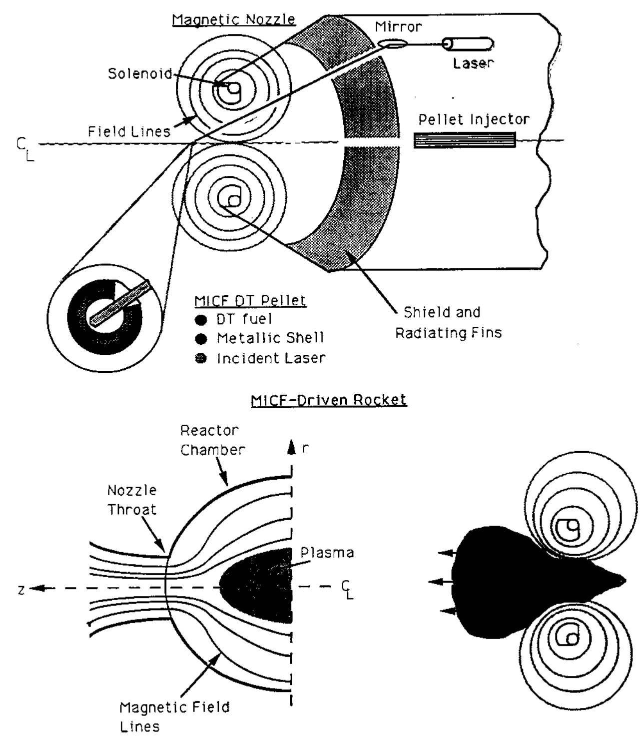


Figure 1: Schematic of (1) Plasma Formation and (2) Magnetic Field Formation in MICF

MICF FUSION PROPULSION SYSTEM



Meridional Magnetic Nozzle

Design of 160 MW$_e$ Nuclear Power System (Brayton)

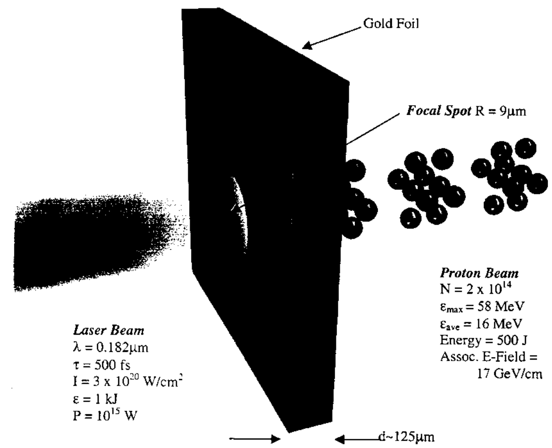
(Lee Mason, NASA GRC)

Masses in kg

System Sizing	Near Term		Mid Term		Far Term	
Reactor/Shielding		121978		102140		79593
(1) Reactor	115307		96163		74399	
(1) Inst. Shield	4923		4386		3694	
(0) Crew Shield	0		0		0	
(1) PHTs	1748		1591		1500	
Power Conversion		17433		15513		14749
(10) TAC/Ducts	182		182		181	
(10) Recuperators	916		805		775	
(10) Coolers	487		424		384	
(10) Structures	158		141		134	
Heat Rejection		110756		42080		8810
(1) Radiator	110756		42080		8810	
(1) Aux. Equip	0		0		0	
Power MGMT & Dist.		534155		161079		77157
(1) Electronics	234756		92061		34709	
(1) Radiator	83137		28696		25592	
(1) PL Rad.	57905		28953		14476	
(1) Cabling	158357		11370		2379	
Total		784322		320813		180309
Ratio	4.9 kg/kW$_e$ = 4.9 mT/MW$_e$		2.0 kg/kW$_e$ = mT/MW$_e$	2.0	1.1 kg/kW$_e$ = mT/MW$_e$	1.1

Laser Accelerated Plasma Propulsion System (LAPPS)

Recent Experimental Results – R.A. Snavely et al, Phys. Rev. Lett., 85, 2945 (2000)

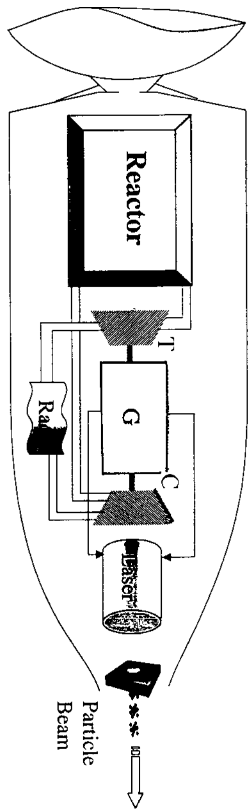


LAPPS Propulsion System
Rep Rate $\omega = 10^3$
$I_{sp} = 5 \times 10^6$
Thrust $F = 1.83 \times 10^{-2}$ N
Driver = Nuclear Reactor ~ 1 MW$_e$
$M_f = 5 \times 10^3$ kg

Fly-By Missions with Above LAPPS
Pluto ~ 56 Years
Jupiter ~ 19 Years
Mars ~ 6 Years

LAPPS with F ~ 1 N
Pluto ~ 7 Months
Jupiter ~ 2.3 Months
Mars ~ 3 Weeks

Laser-Accelerated Plasma Propulsion System (LAPPS)



CONCLUSIONS

1. Non-chemical propulsion is needed for Human/Robotic Exploration of the Solar System.
2. Nuclear Thermal propulsion can generate I_{sp} ~ 900 seconds and sizable thrusts but inadequate for deep solar missions.
3. NERVA technology is available and Lox-Augmented systems are feasible, but fuel temperature limitations constitute the major obstacle.
4. Fusion propulsion can generate very large I_{sp} ~10^5 seconds at Moderate-Sizable thrusts.
   i. Magnetic mirror machines are perhaps best understood physics-wise, can be sizable and massive but there are clever schemes for drastically reducing the mass.

As propulsion systems, physics constraints are less stringent than Terrestrial power systems.

ii. Inertial fusion can produce high I_{sp} and sizable thrust. They require large power source (e.g. nuclear reactor) to drive them. They do however lend themselves to antiproton-catalyzed fusion for which the mass will be drastically reduced.

5. Nuclear-Electric e.g. "Laser-Accelerated plasma propulsion Systems (LAPPS)" can produce I_{sp} ~10^6 seconds at very modest thrust. Requires a nuclear reactor to drive it but has the potential of producing sizable thrusts to make it especially suitable for Human/Robotic Exploration of Solar System.

Rapid progress is being made in this field to make it a strong candidate for this mission in the time frame of 10-40 years.

6. Very encouraging progress is also being made in space nuclear power from the nuclear reactor design to the heat rejection system to make all of the above candidates feasible in the time frame of interest.